BY GLEN BRISEBOIS • LINEAR TECHNOLOGY CORP

Signal conditioning for high-impedance sensors

MAINTAINING ACCURACY IN CIRCUITS THAT PROCESS SIGNALS FROM HIGH-IMPEDANCE SENSORS PRESENTS UNIQUE CHALLENGES. FIRST, YOU NEED TO IDENTIFY WHEN TO USE SPECIAL DESIGN TECHNIQUES. THEN, YOU MUST CHOOSE DEVICES THAT BUFFER AND PROTECT THE SENSORS AND CIRCUITS WITHOUT DESTROYING THEIR ACCURACY.

If you had the option, you probably wouldn't use high-Z (high-impedance) sensors. Their sensitivity to external noise, solder-flux residue, particle tracking, bias currents, and distant charges can make repeatable measurements difficult. High-Z sensors have an upside, though: They don't self-load, and they inherently use little power. For certain variables, such as pH, light, acceleration, and humidity, the most practical sensors are high-Z devices. Because nature offers them, expediency urges their use. Careful attention to design can minimize the devices' tendency to receive adverse effects from the world around them. As an interesting note, with the advent of practical superconduction, impedance values have achieved an infinite range.

When you make measurements to characterize the behavior of any circuit that processes signals from high-Z sensors, you should drive the circuit's inputs through a high Z or a high resistance. Every engineer who works with signal conditioners for high-Z sensors should have some high-value reference resistors at hand. Vishay (www.vishay.com) offers surface-mount resistors with values to 50 GΩ. Samples with values of 1 and 2 GΩ were available off the shelf at press time. The Mini-Mox series from Ohmite (www.ohmite.com) contains leaded 10- and 100-GΩ resistors. All of these high-value resistors are remarkably "stiff" (conductive, nonisolating). For example, a colleague warns users not to touch the resistor bodies, lest skin-oil deposits reduce the impedance.

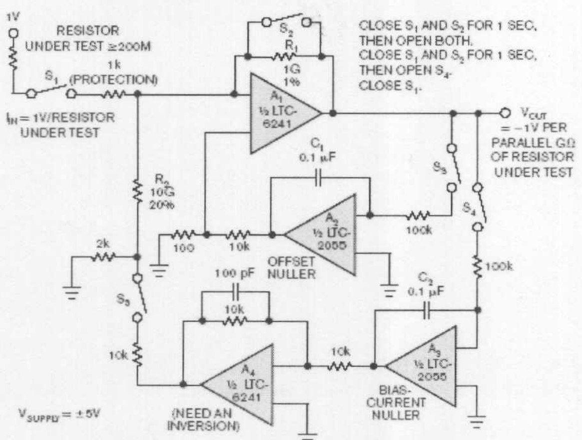

Figure 1 Using nulling techniques is tempting, and you can sometimes make them work with much effort and shielding. But making a "perfect" amplifier like this one becomes expensive and departs from the high reliability of solid-state design. You may be bankrupt before your design reaches production.

This warning suggested an experiment. Connecting a Keithley (www.keithley.com) Model 614 electrometer across the resistor leads resulted in a meter reading of 9.9 to 10 GΩ. After thoroughly touching and squeezing the resistor body from lead to lead with oily fingers and then backing away, the meter returned to precisely where it had been: 9.9 to 10 GΩ. This test shows only that skin oils are not an immediate threat to these resistors. To ensure reliability over time and humidity, sound laboratory practice still exhorts keeping components, pc boards, and insulators clean. Skin-oil conductivity is known to vary among individuals. For cleaning, Ohmite recommends using isopropyl alcohol and lint-free wipes and baking the device at 75°C for one hour to drive off moisture. When performing an impedance measurement of this type, bear in mind that the insulator in the cable is entirely in parallel with the resistor under test. Limiting error to 1% in a 100-GΩ-resistor measurement requires an overall insulator impedance of no less than 10 TΩ. The only way around this limitation is to perform an open-circuit calibration to measure and mathematically remove any shunt resistance. The Keithley 614 lacks this feature, but it still performs well, reinforcing the idea that, compared with an insulator, a 10-GΩ resistor is indeed relatively stiff.

ENEMIES OF HIGH-Z CIRCUITS

When Z is high, leakages, current noise, bias currents, and static voltages dominate the errors, so dealing with high-Z circuits means minimizing those quantities. The most common and addressable form of leakage is solder-flux residue. Carefully clean any board that supports high-Z circuits to remove all flux. Washers that board manufacturers use can be contaminated. Space traces beyond the minimum design rules to the extent that board area allows. For insulators, FR-4 usually causes no problem,

although, unlike Teflon and glass, it does absorb moisture. Some designers have had success with Teflon posts or wells, but the good results may be due to these components' inherent resistance to surface tracking and other effects, such as dielectric absorption, rather than their purely insulating properties. Keeping surface impedances high in imperfect environments may require sealing or conformal coating, but such measures can reduce serviceability. Guard traces connect to high-Z sources with traces at similar potentials. Through-hole pins should have guard traces on all or at least on the outside layers. There are many practical considerations. For example, a dual op amp has noninverting inputs on pins 3 and 5. It is easier to guard Pin 5, because it is in the corner; Pin 3 is next to the negative supplies.

Bias current and current noise in active devices are sources of error. Bipolar transistors require dc base currents to operate; FETs have input leakage. In both cases, electron quantization through junctions induces current noise. (Such noise is present only in currents that flow through junctions.) In FETs, current noise rises with frequency because of Miller effects (see sidebar "Current-noise measurements" with the Web version of this article at www.edn.com/ms4177). Although you may want to jump immediately to FET-based input structures for their low bias currents, superbeta bipolar input structures can offer advantages, particularly in high-temperature operation. FET-input leakage doubles every 10°C, whereas superbeta bias current remains relatively stable. In either case, chopping techniques can remove the effects of both offset voltage and bias current. For impedances of less than a few megaohms, don't jump immediately to a FET-input amplifier without first considering exceptionally precise, low-bias-current op amps, such as Linear Technology's LT6010 or LTC2054. Sometimes, a lower offset voltage can be more important than a lower bias current.

For a given source impedance, the overall input error is $V_{OS}+I_{BIAS}\times R_{SOURCE}$. As the source impedance rises, the bias-current term dominates, making a MOSFET input more attractive. MOSFET inputs have in recent years gained popularity as CMOS-op-amp specifications have improved.

Another problem with high-Z circuits is their sensitivity to motion. Shoes rubbing against a carpet can generate static charges that can reach kilovolt levels, so even the tiniest capacitive coupling can inject significant charge. When taking measurements, stand back and hold still. Shielding helps, of course, but mechanical vibrations (microphonics) modulate the capacitance between pc-board traces and any local metalwork, causing charge injection—even if the metalwork does not change in voltage but simply stays at a dc voltage different from that of the traces. So shield your circuit, but not too closely.

When mechanical motion or stress induces tiny voltages on insulators, triboelectric or piezoelectric effects occur. In high-vibration environments, high-Z sources may require low-triboelectric-noise cable, such as Belden (www.belden.com) type 9239.

DEVICE AND AMPLIFIER CONSIDERATIONS

Although discrete MOSFETs offer poor leakage specifications, the devices can outperform their specifications by as many as six orders of magnitude. The familiar 2N7002, for example, specifies maximum channel leakage of 1 mA and gate leakage of 0.1 mA. But if you look at these devices in the lab with 20V on

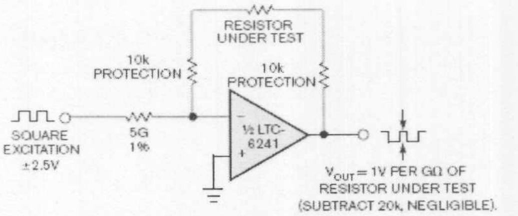

Figure 2 You can more easily achieve similar accuracy with chopped-excitation techniques. The amplifier's characteristics are not enhanced but rather measured and subtracted. What are the op amp's offset and bias current? It doesn't matter much.

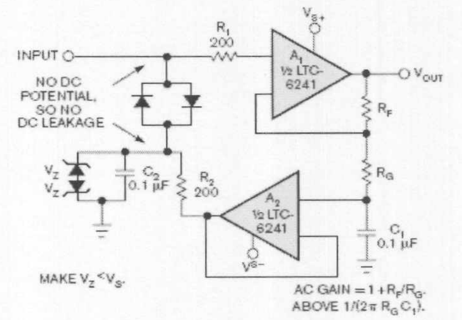

Figure 3 The tracking clamp has protection diodes, but A_2 back-drives them to the same voltage as the input. The zener diode and its capacitor carry most of the clamp current. R_1 and R_2 keep current away from the amplifiers.

the drain and a grounded gate and source, you find a total combined leakage of only about 1 pA. Obviously, the specifications do not reflect what the device does, but rather the cost of production-test time. Tighter specifications require more test time and better test equipment, for which you pay. Of course, tighter specifications also tend toward lower yield; you pay for that, too.

Ultralow-leakage matched-pair JFETs include the LS830 from Linear Integrated Systems (www.linearsystems.com) and the IFN124 from InterFET (www.interfet.com). A favorite single JFET is the Philips (www.semiconductors.philips.com) BF862 because of its 3-pA gate current, its subnanovolt noise density, and its easy-to-deal-with 0.6V pinch-off voltage. The 2N4416 is also popular, especially for its subpicofarad input capacitance and respectable noise density, but many designers have found troublesome JFETs' large and widely varying 2 to 6V pinch-off voltage.

CMOS op amps have for many years been available, but the specifications have been poor, and the actual results, even worse. Linear Technology has just introduced the precision micropower LTC6078 and the higher speed LTC6241 CMOS op amps. The LTC6241 offers a typical input-leakage current of 4 pA at 70°C. JFET-input-based electrometer-grade op amps have for many years been on the market but are relatively expensive. In the end, no op amp or semiconductor device is perfect, and some designers find that they can achieve the best dc results with relays and calibrating or chopping techniques.